Government College of Engineering and Research, Avasari(Khurd)

Department: Mechanical Engineering

Learning Resource Material (LRM)

Name of the course: Engineering Metallurgy **Course Code:** 202048

Name of the faculty: J. M. Arackal **Class:** SE(Mech)

SYLLABUS(Unit 4)

Unit IV: Heat- treatment Of Steels (6 Hrs) Transformation products of Austenite, Time Temperature Transformation diagrams, critical cooling rate, continuous cooling transformation diagrams. Heat treatment of steels: Annealing, Normalising, Hardening & Tempering, quenching media, other treatments such as Martempering, Austempering, Patenting, Ausforming. Retention of austenite, effects of retained austenite. Elimination of retained austenite (Subzero treatment). Secondary hardening, temper embrittlement, quench cracks, Hardenability & hardenability testing, Defects due to heat treatment and remedial measures.

Classification of surface hardening treatments, Carburising, heat treatment after Carburizing, Nitriding, Carbo-nitriding, Flame hardening, and Induction hardening.

Lecture Plan format:

Name of the course: Engineering Metallurgy **Course Code** 202048

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Unit No	Lecture No.	Topics to be covered	Text/Reference Book/ Web Reference
		Unit 4: Heat- treatment Of Steels	
4	1	Transformation products of Austenite, Time Temperature Transformation diagrams, critical cooling rate	1,2
4	2	Continuous cooling transformation diagrams. Heat treatment of steels: Annealing, Normalising,	1,2
4	3	Hardening & Tempering, quenching media, other treatments such as Martempering, Austempering, Patenting, Ausforming. Retention of austenite, effects of retained austenite.	1,2
4	4	Elimination of retained austenite (Subzero treatment). Secondary hardening, temper embrittlement, quench cracks, Hardenability & hardenability testing	1,2
4	5	Classification of surface hardening treatments, Carburising	1,2
4	6	Heat treatment after Carburizing, Nitriding, Carbo-nitriding, Flame hardening, and Induction hardening	1,2

List of Text Books /Reference Books/ Web Reference

1- *Material Science & Metallurgy For Engineers", Dr. V.D. Kodgire & S. V. Kodgire , Everest Publication.*

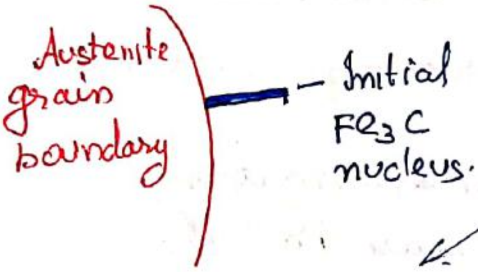
2- *Introduction to Physical Metallurgy, Avner, S.H., Tata McGraw-Hill*

Unit:4 → Heat Treatment of Steels

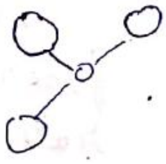
Transformation products of Austenite

1) Transformation of Austenite to Pearlite

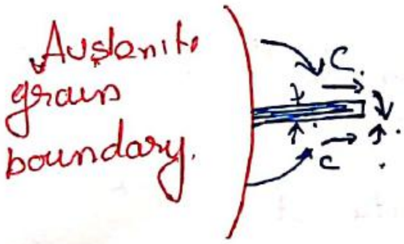
Pearlite transformation starts by nucleation of cementite plate at the grain boundaries of homogeneous austenite.

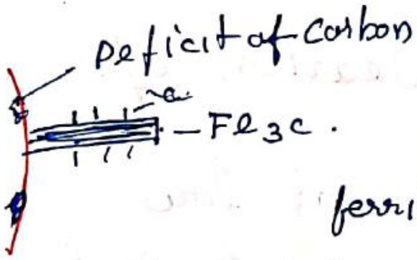


During their growth, carbon from Austenite matrix diffuses towards its flat faces.

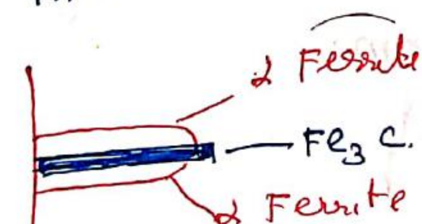


This process reduces the carbon in the adjacent region of growing cementite plate.





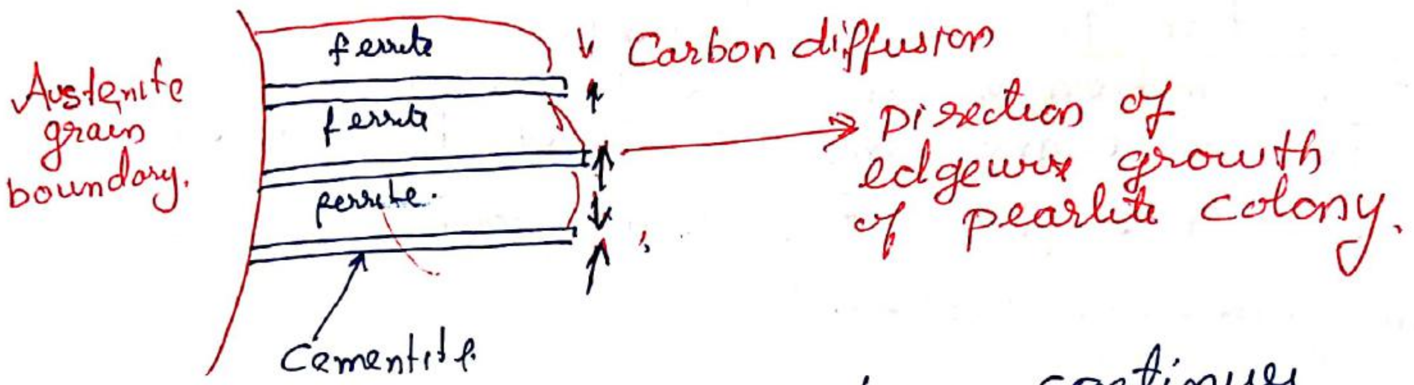
When the carbon reduces to a critical value, two ferrite plates, one on either side of the cementite plate nucleate in this carbon deficient region.



These ferrite plates grow by rejecting carbon in excess of their solubility limit to the adjacent Austenite.

The rejected carbon then helps to nucleate new parallel cementite plates on both sides, & the process is repeated.

→ New Fe_3C nucleus of different orientation.

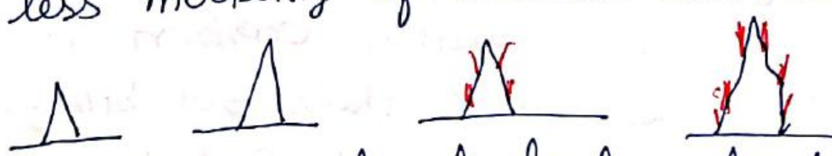


growth of any one colony continues till it infringes on other growing colonies.

Lower the temperature of transformation, finer is the pearlite (Due to increase in the rate of nucleation).

II). Transformation of Austenite to Bainite

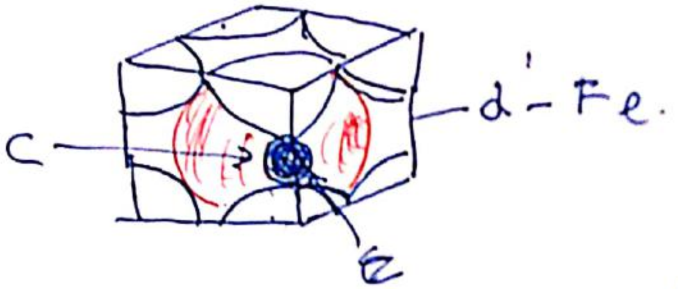
- occurs below 550°c.
- Extremely fine mixture of ferrite & cementite
- The process starts by nucleation of ferrite.
- The transformation occurs at low temperature, so nucleation rate is high but growth rate is low due to relatively less mobility of carbon atoms.



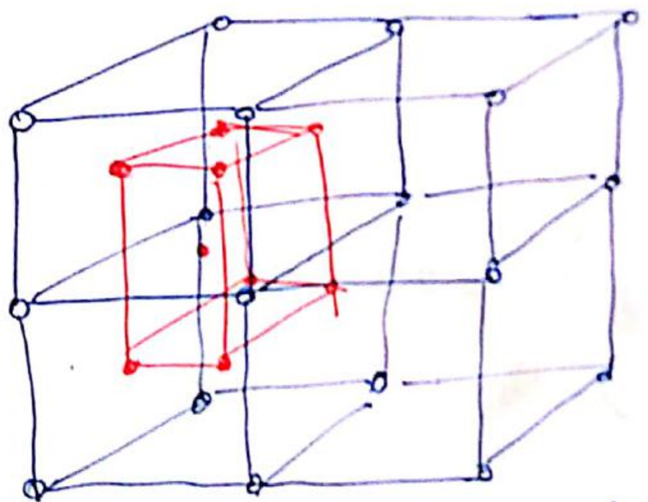
Bainite formed at higher temperature is called upper bainite & has a feathery appearance, whereas the bainite formed at lower temperature is called as Lower bainite & is harder, stronger & tougher than upper bainite.

Transformation of Austenite to Martensite

Austenite very transforms to martensite by shear mechanism involving no diffusion & the transformation proceeds at a speed close to speed of sound.



The presence of carbon in austenite & inhibits the complete alteration of the lattice.



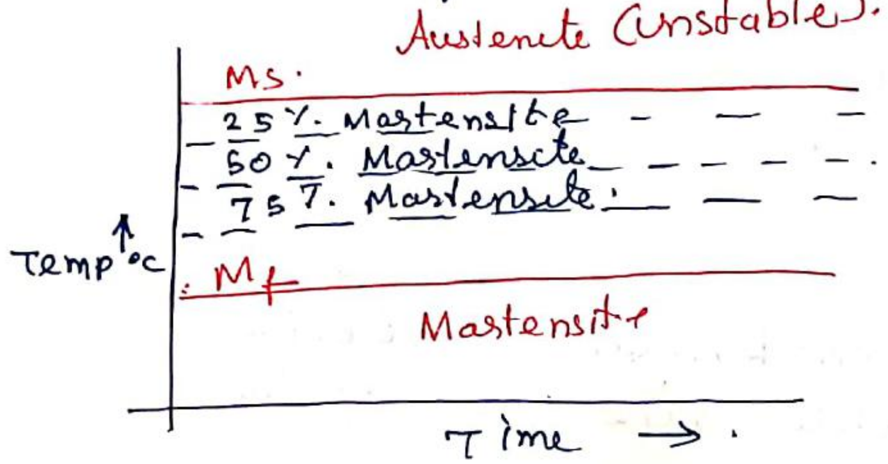
Excess carbon atoms are trapped & are unable to diffuse out of Austenite FCC.

BCT unit cell is outlined within FCC unit cells

The amount of Carbon in austenite is not sufficient to fill all the octahedral sites in every unit cell of martensite.

Martensite is a metastable structure. & is very hard, strong & brittle.

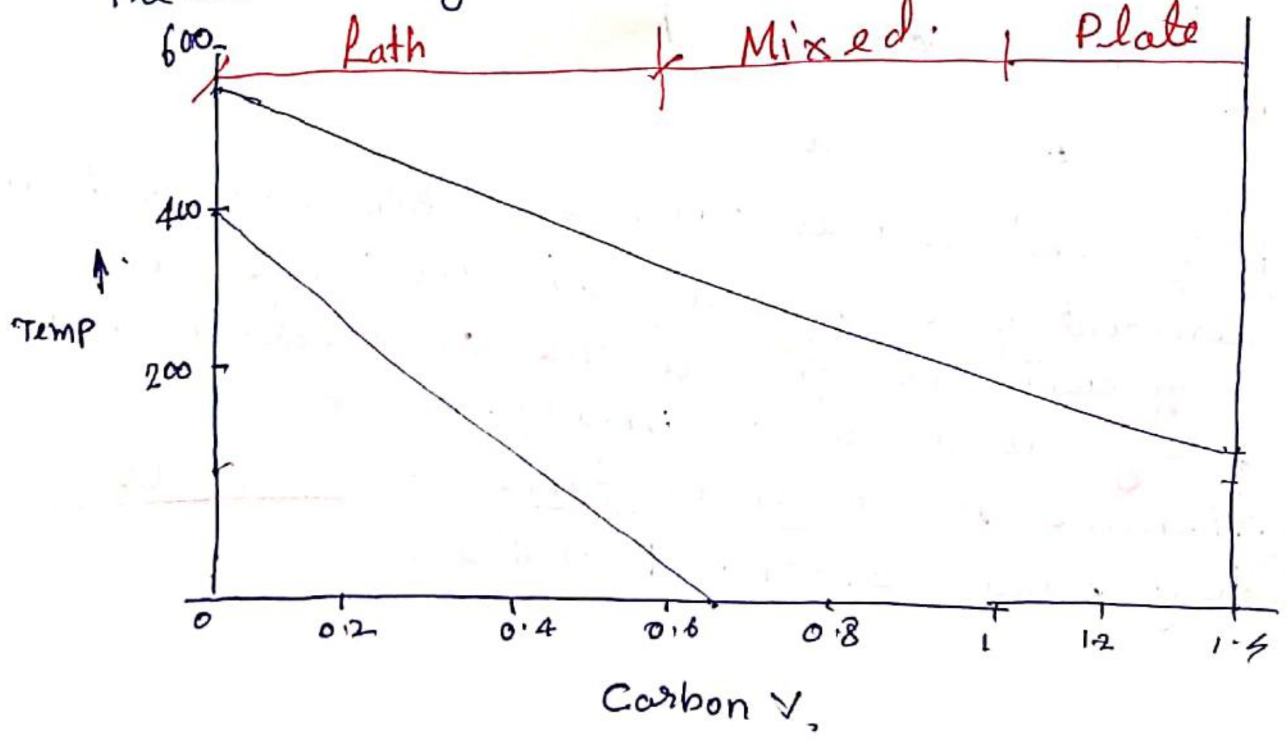
During cooling Austenite starts transforming to martensite at some temperature, denoted as M_s (martensite starts) temperature & when almost 99% austenite transforms to martensite, its denoted as M_f (martensite finish).



The austenite which has not transformed to martensite is called retained austenite or untransformed austenite.

M_s & M_f depends on the carbon & alloying elements present in steel.

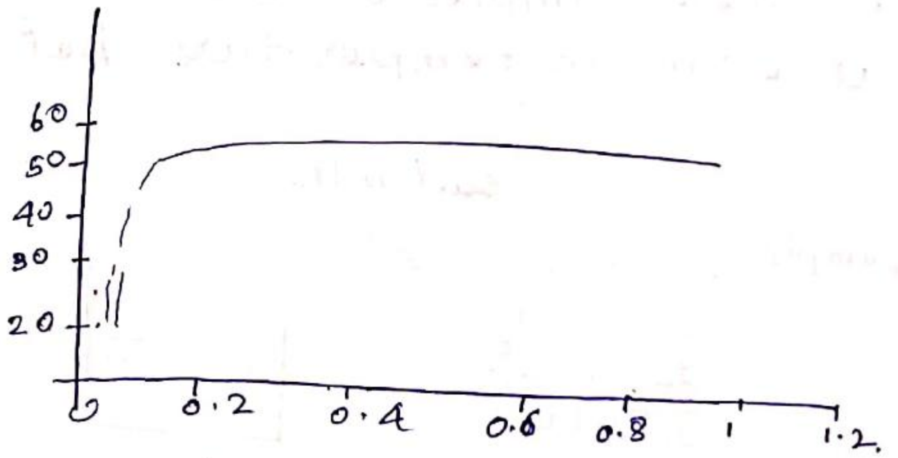
The usual range is 150 to 215°C.



1. For Carbon above 0.7% C, M_f is below room temperature so there will be retained Austenite, Austenite is soft

Martensite occupies greater volume, volume increases by 2 to 5%. depending on the carbon content & alloying elements. This may lead cracking, but this tendency is reduced due to the presence of Austenite (retained).

The retained Austenite may get transformed to Bainite or Martensite under certain conditions, resulting in volume changes, which is undesireable for precision gauges and measuring instruments.



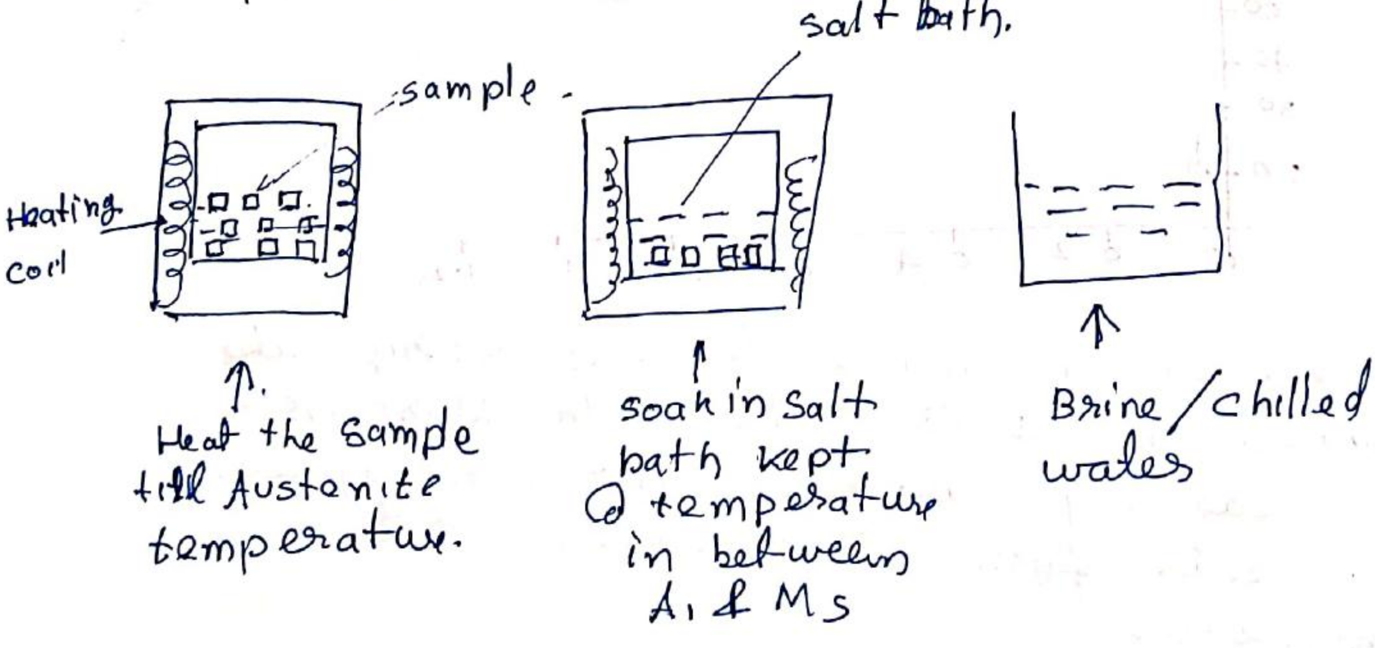
Low carbon martensite has strip like appearance & is called Lath Martensite whereas high carbon martensite appears in needle form & is called Plate martensite.

Time Temperature Transformation

These diagrams indicate the phase existing in steels at various temperatures & times & are useful in heat treatment of steels

Determination of TTT diagrams:

1) Heat large numbers of ~~stell~~ steel pieces of suitable size, maintain the austenizing temperature. oxidation & decarburization should be avoided by suitable measures. such as by use of salt baths
2) Soak these samples for sufficient time so as to obtain homogeneous austenite. The time of soaking should be kept constant
3) Transfer all these samples to salt bath maintained at constant temperature between A_1 & Ms.

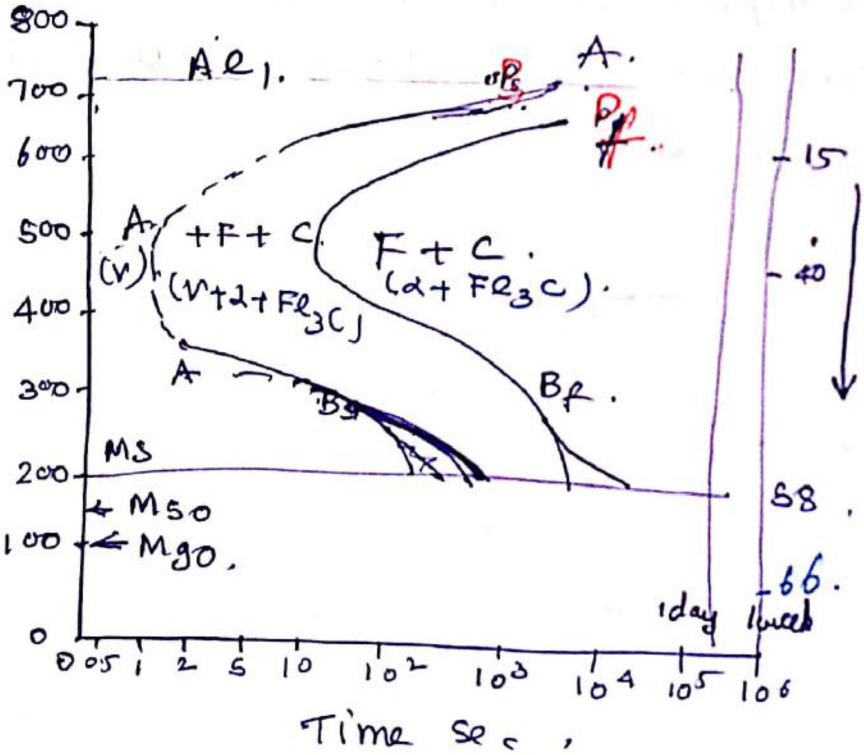


4) Remove these sample one by one at equal/fixed interval of time & quench in brine or cold water. Due to this untransformed Austenite will convert to martensite.
5) Find out the start & end time of transformation at all temperatures.

Eutectoid steel will have. Pearlite start & finish time. 4.

for off - eutectoid, there will be time for. pro eutectoid ferrite & cementite.

The resulting diagram is called Time - Temperature Transformation (TTT) diagrams it also called Isothermal transformation, because of its shape. its also called C or S curve



Hardness Rc.

Hardness

Martensite > Bainite > Pearlite.

Un·

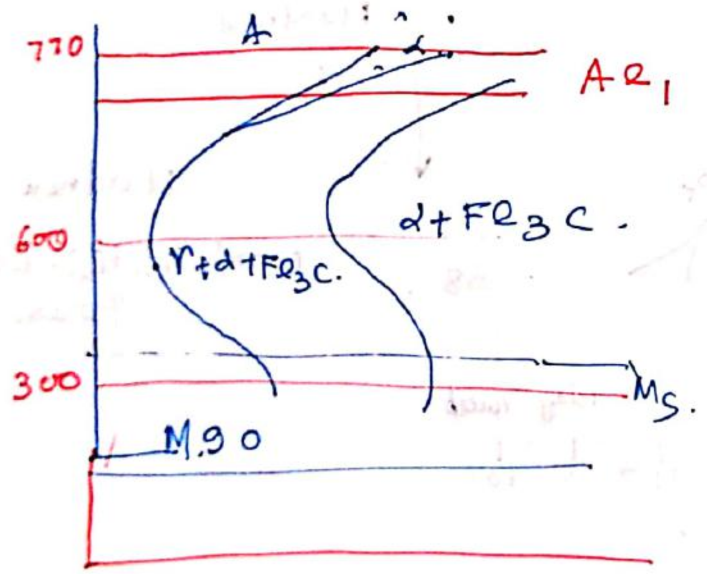
Impact of Carbon on T T T.

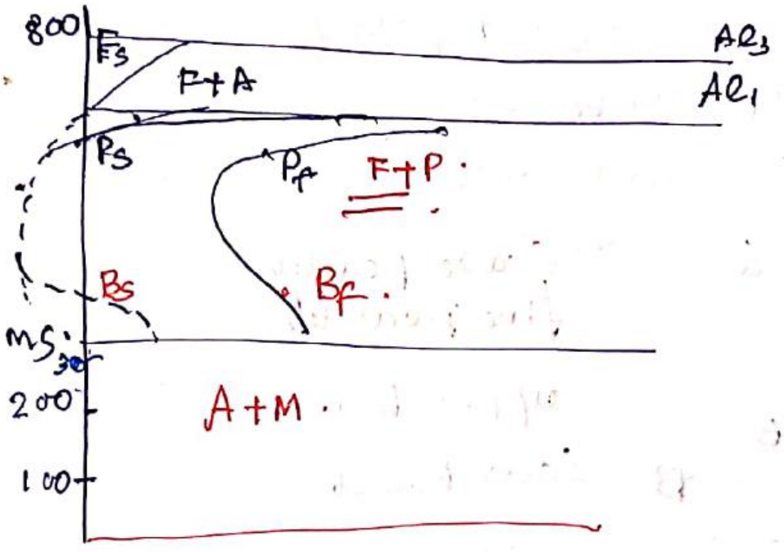
i) The nose of S curves for hypo & hyper-eutectoid steels are closer to the temperature axis, so faster cooling rates are required.

ii) Carbon content has minor impact/effect on the time required for the pearlitic reaction.

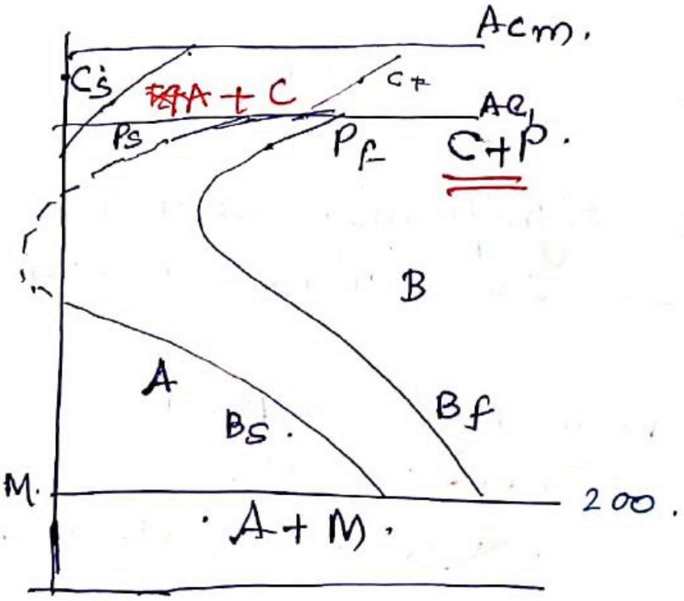
iii) Dissolve carbon greatly retards the initiation & completion of bainite reaction

iv) Dissolved carbon stabilizes austenite & reduces Ms temperature.





Hypo eutectoid steel (0.35 % Carbon)



Hyper eutectoid steel (1.1% steel).

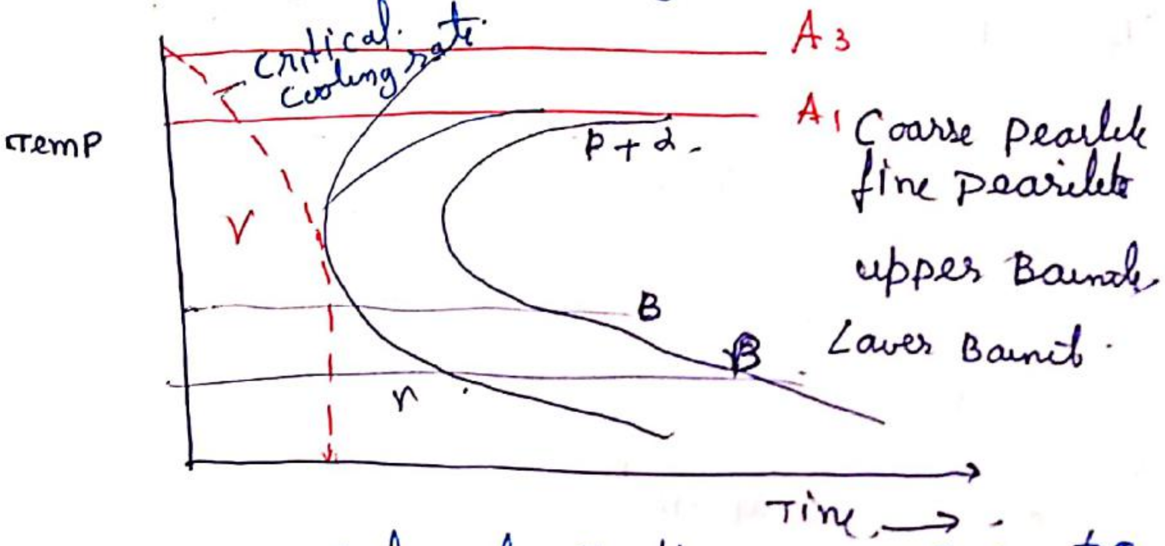
The transformation product between the nose temperature & Ms is bainite.

The morphology of bainite below the nose is feathery & above Ms is acicular.

Pearlite is relatively soft, bainite is medium hard & Martensite is hard.

Critical Cooling rate

Its the rate that passes (just passes) through the nose of the IT diagrams.



The rate of cooling necessary to just suppress diffusion transformation is called as CCR.

Less the critical cooling rate more is the hardenability

Alloying elements significantly reduce CCR, so steel with 5% Cr can be hardened by air cooling

Low CS have very high CCR & hence rapid cooling is necessary.

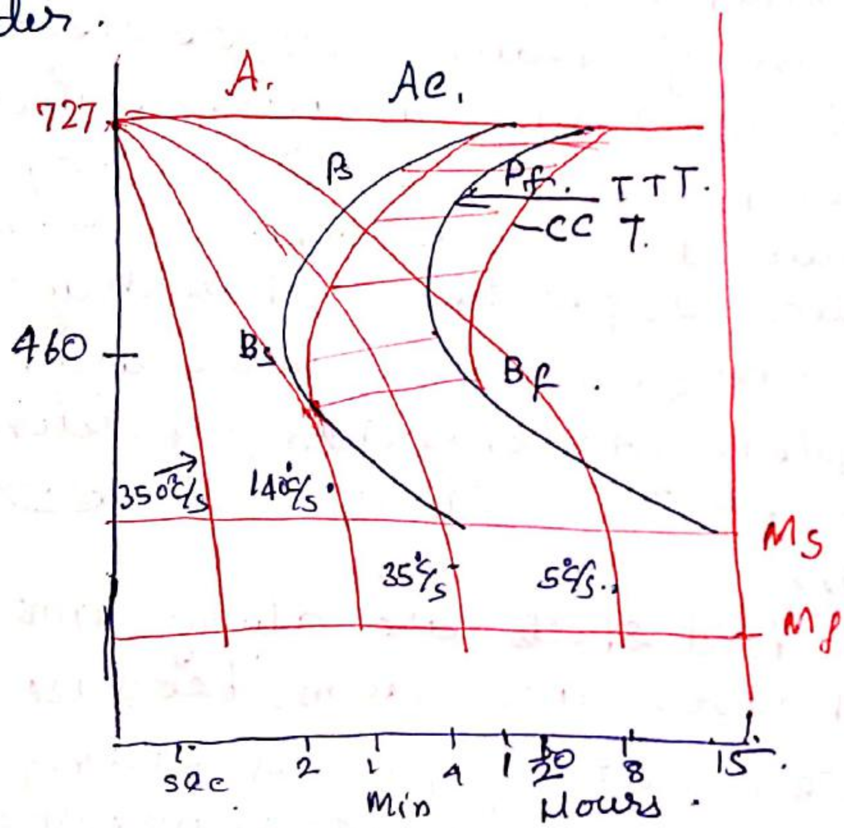
Some may not even undergo hardening

Continous Cooling Transformation Diagrams

In this process steel is not cooled isothermally but cooled continously.

So TTT curve shifts to the right & also downward.

The specimen are heated to Austenite region & cooled with a constant rate to some definite temperature & quenched in water.



Four different cooling rates are shown.

Rate II → Critical cooling rate.

Rate III → some pearlite

Rate IV → Complete pearlite

Heat Treatment of Steels

Conventional Annealing. (Full Annealing)

Purpose.

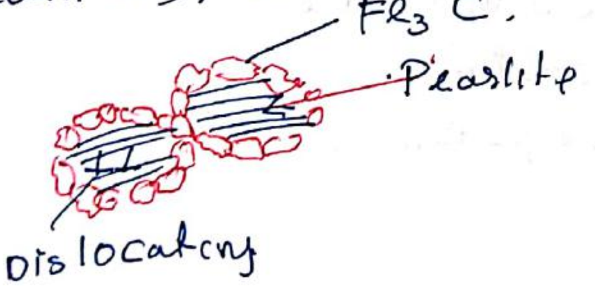
i) Releive Internal stress due to cold workings
ii) Increase Ductility
iii) Increase uniformity of phase distribution
iv) Refine grain size.
v) Increase machinability

The process consist of heating hypoeutectoid steel above A_3 temperature & hypereutectoid steels above A_1 temp. by 30 - 50°c. holding at this temperature & slow cooling. This ensures eutectoid reaction as per Fe-C phase diagram.

To ensure equalization of temperature throughout. (Complete Austenization) holding period of atleast 20 min / cm of thickest section is needed.

* Hypereutectoid steels are alway annealed from above A_1 & never above Acm, because.

1) Proeutectoid cementite seperates along grain boundaries of Austenite (transforms to pearlite); so dislocations get blocked.



2) Acm temperatures are high, so it results in oxidation & decarburization

Cooling media

Brine (Cold water + 5 to 10% Salt) — Sodium chloride or calcium chloride

Cold water.

water + Soluble oil.

Oil.

Fused salts

Air.

Bright Annealing

Done using some protective medium to (Inert gas) Prevent oxidation & surface discolourisation such a type of annealing keeps the surface bright. hence its called Bright annealing [15% H_2, 10% CO, 5% CO_2, 1.5% CH_4 & remainder N_2].

Box Annealing

Carried out in a sealed container to minimise oxidation. Components are packed with charcoal or clean sand.

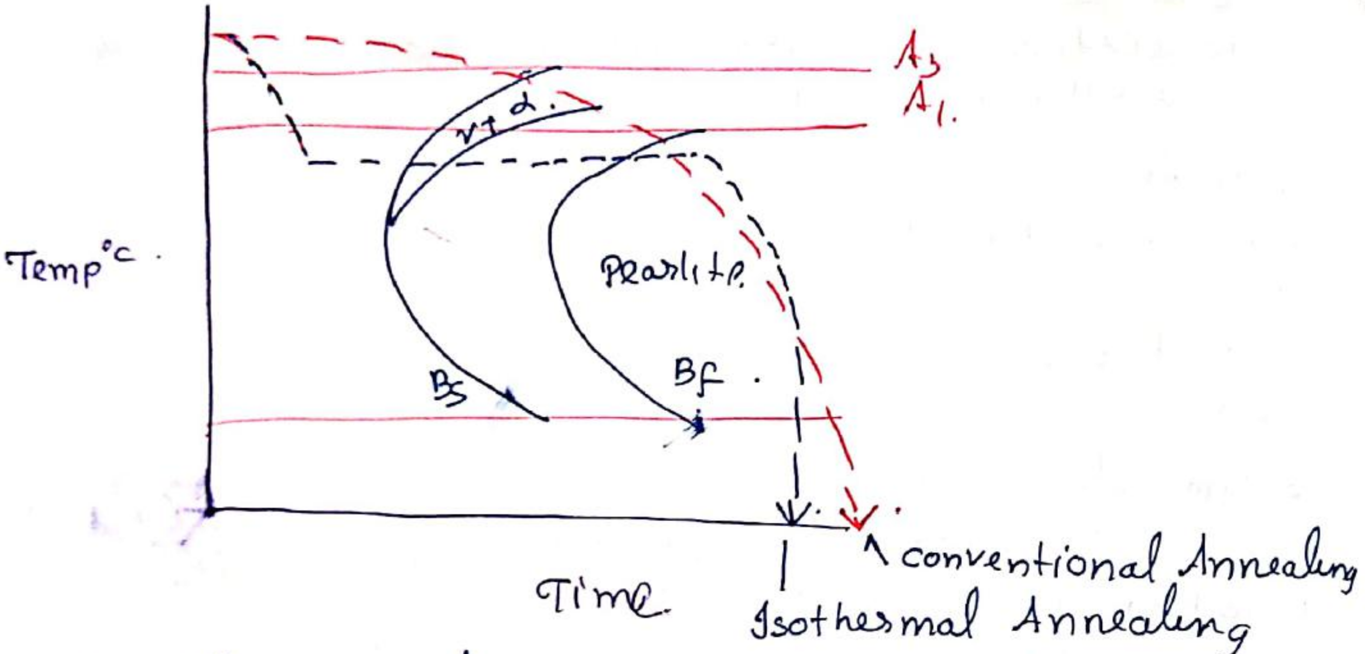
Its also called black annealing, close annealing or pot annealing

Isothermal Annealing (cycle).

Held at A_1 for some time & then cooled to room temperature.

It has following advantage compared to full/Conventional Annealing.

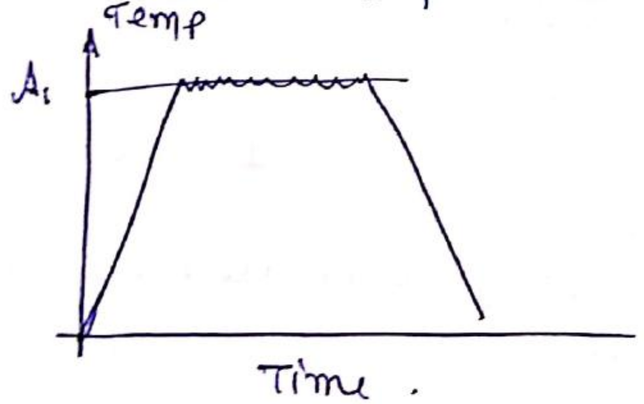
1) Reduces Annealing time.
2) Because of equilization of temperature, transformation occurs at same time throught the crossection.
3) Improved machinability



Spheroidise Annealing

given to high carbon & air hardening alloy steels to soften them & to increase machinability:

Due to holding at just below the lower critical temperature, cementite from pearlite globularises. This process is very slow.



subcritical Annealing: Cold worked steel heated to some temperature below lower critical temperature.

used for releiving internal stresses or to reduce hardness or refine & modify the structure.

Normalising:

The process is used to eliminate the cementite network that may have formed due to slow cooling in temperature range.

The process consist of heating to above the upper critical temperature (A_3) for hypoeutectoid & above Acm (or between A_1 & Acm) for hypereutectoid by 30-50°c. holding it long for homogeneous Austenization followed by cooling to room temperature in still air.

Air cooling is faster than furnace cooling

Annealed	Normalised
1) Less hardness, Tensile strength & toughness.	- comparatively more hardness TS & toughness
2) Microstructure shows pearlite in accordance with FeC	2 Microstructure shows more pearlite.
3) Coarse pearlite	- fine pearlite
4) Internal stresses are least	- Internal stresses are more (slightly)
5) grain size distribution is more uniform.	- grain size distribution is slightly less uniform.

Hardening

Purpose:

1) Harden steel to the maximum level by Austenite to martensite transformation.
2) Increase wear resistance & cutting ability of steel.

i) Conventional Hardening:

Heating steel above A_3 temperature for hypoeutectoid steel & above A_1 temperature for hypereutectoid steel by 50°C, austenitising for sufficient time & cooling with a rate exceed critical cooling rate so as to obtain martensite.

Hypoeutectoid is always hardenend above A_3 to avoid proeutectoid ferrite.

Hyper eutectoid is always hardened in between A_1 & A_{cm}; so as to obtain Fe_3C along with Martensite

If these steels are hardened above A_{cm}, the following drawbacks are observed.

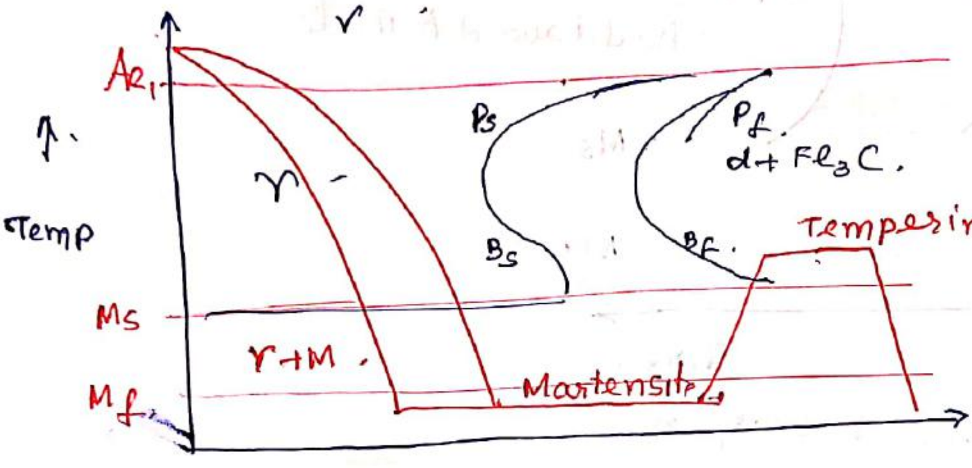
1). Absence of Fe_3C above A_{cm} leads to coarse grained martensite which is extremely brittle.

ii) Quenching from such a temperature results in more distortion.

iii) Higher temperature causes oxidation & decarburization.

iv) Retained Austenite increases.

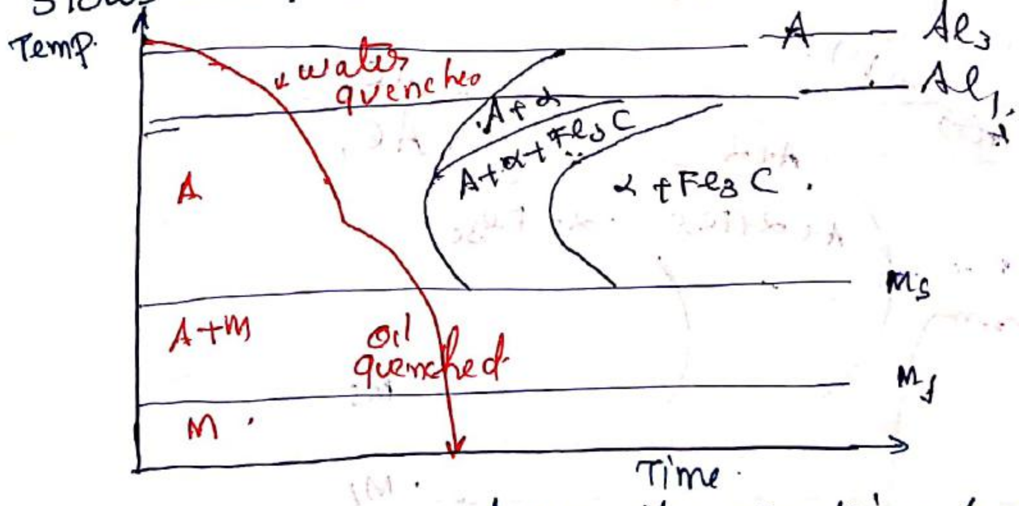
Alloy steels have lesser cooling rate → air cooling (9.)
High C.S have slightly more CCR → Oil quenching
Medium CS have higher CCR → water / brine



Heat treatment cycle for conventional Hardening (Eutectoid steel).

(ii) The timed quench (Interrupted quench).

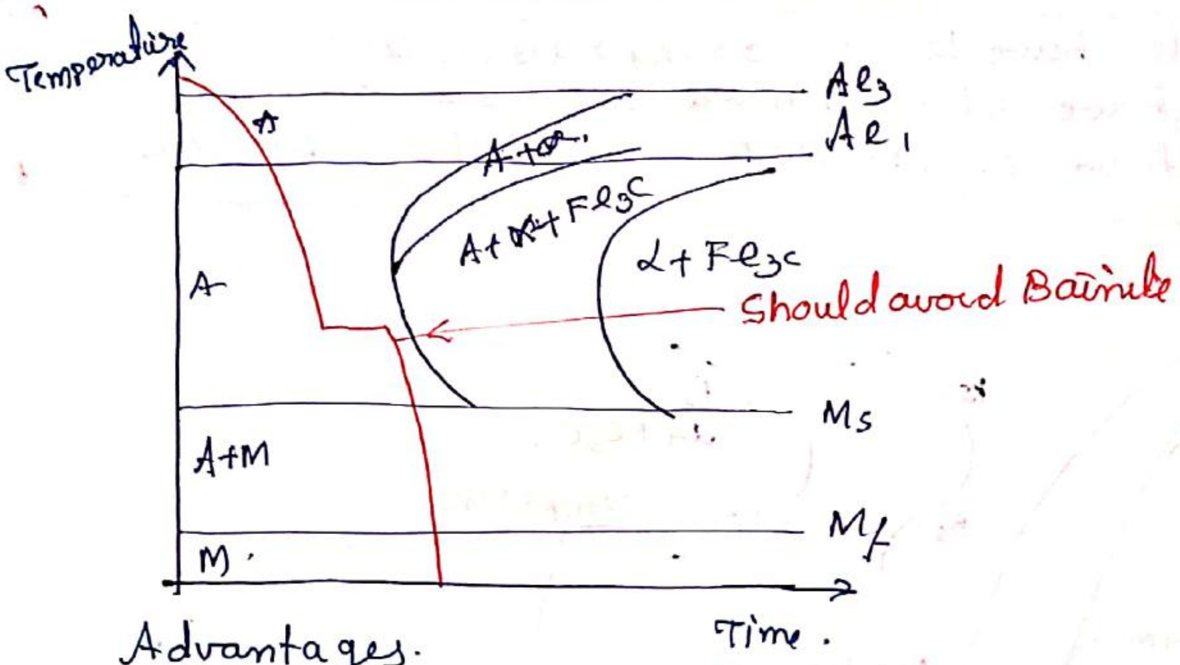
For plain CS, high CCR is needed. But after nose of the curve transformation slows down, so two cooling rates are employed.



This process reduces the cracking tendency.

(iii) Martempering (Marquenching).

Austenized steel is cooled rapidly avoiding nose of the IT diagram (between nose & Ms). soaked at this temp for sufficient time. & then cooled to room temperature in air or oil.



Advantages.

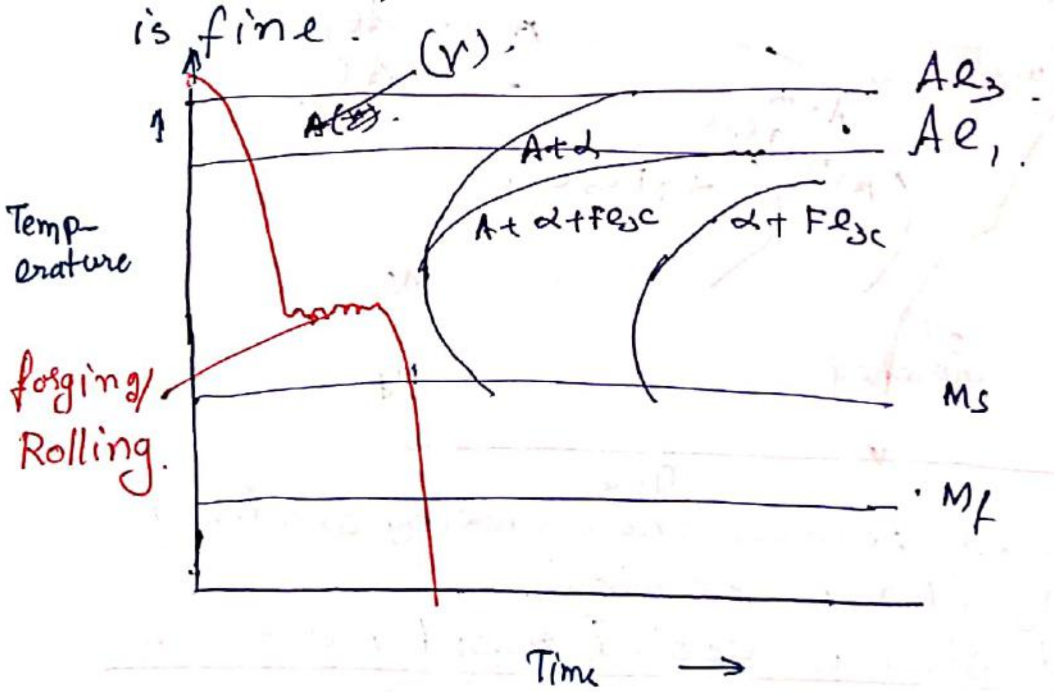
1) Less distortions & warping.

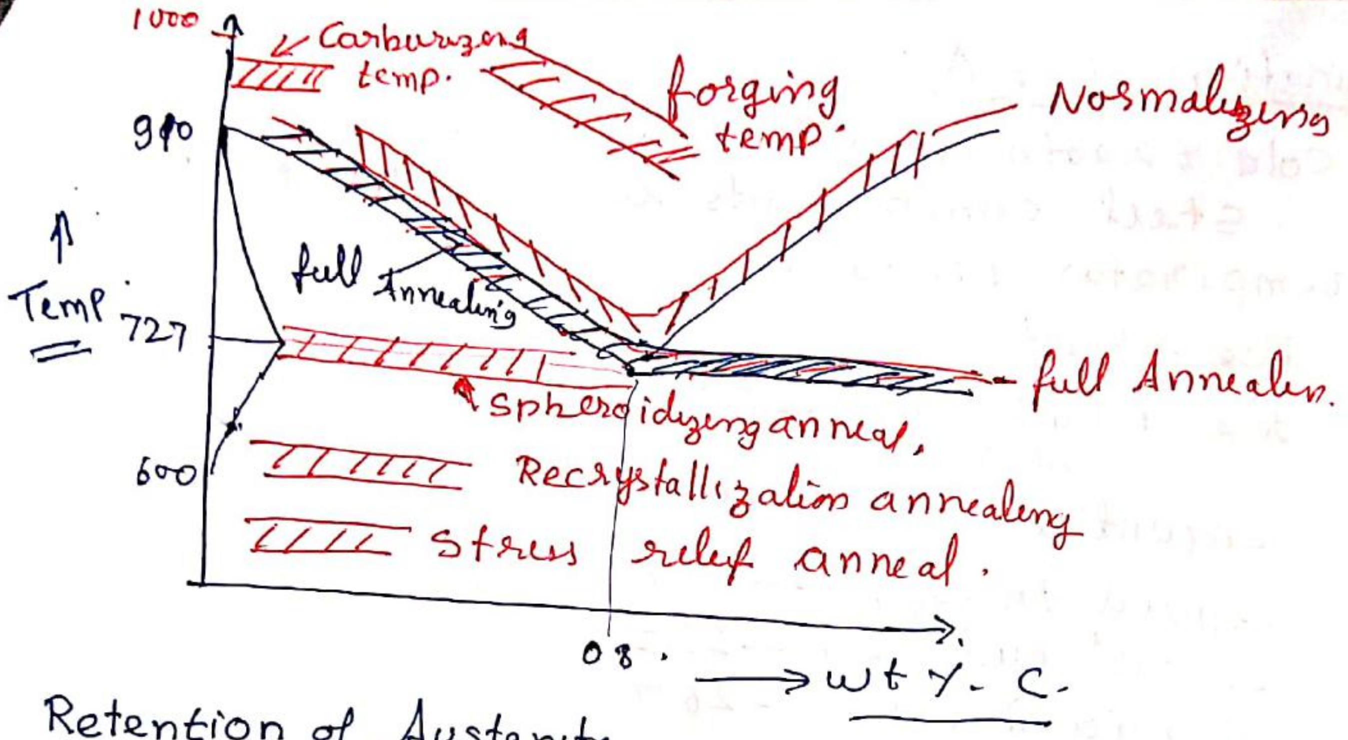
11) Less cracks.

iv) Ausforming.

Steel is cooled with a rate exceeding CCR, to a temperature between nose & Ms, forged & rolled at this temperature & cooled to room temperature in oil.

Due to plastic deformation martensite formed is fine.





Retention of Austenite

As steel is cooled to some temperature below Ms a certain amount of Martensite forms in the austenite.

Formation of Martensite is accompanied by volume expansion. which develops highly compressive stresses in the austenite opposing its further transformation to martensite.

when steel is cooled to some lower temperature, both phases will contract & process continues, Below Mf 1% Austenite remains in the steel. in a highly compressed condition.

Advantages of Retained Austenite

i) Tendency of cracking is reduced.

ii). If RA is more, such as 30-40%. steel can be cold worked without cracking.

Disadvantages of Retained Austenite

i) Hardness is reduced.

ii) It may get transformed to Bainite at room temperature.

iii) RA is not desirable in tool steels.

Elimination of RA

i) Cold treatment (Subzero treatment).
steel components are cooled to a temperature below M_f

Ice + Salt	-23
Ice + Calcium chloride	-55
Liquid air	-183
Liquid Nitrogen	-196
Liquid hydrogen	-253
Liquid helium	-269

RA will get transformed to martensite

ii) Plastic deformation:
Plastic deformation of Austenite can induce Martensitic transformation this phenomenon is called deformation (strain) induced martensitic transformation

iii) Tempering:
Heating the hardened steel to some temperature below A_1 & then cooling to room temperature.

Tempering.

Purpose

i) To releive internal stresses developed due to rapid cooling of steels during hardening process. (Austenite to martensite) & due to volume changes occuring in the above transformation.

ii) To reduce hardness & increase ductility & toughness

iii) Eliminate Retained Austenite.

Process

Heat the hardened component to ~~about~~ between 100°C & 700°C [below A_1] holding at this temperature for specific period (1-2 hrs) & cooling to room temperature, usually air.

Martensite & Austenite are not stable & try to transform to more stable phase during heating.

Tempering is classified in following types.

i) Low temperature tempering. [100 – 200°C]

ii) Medium temperature tempering. [200 – 500°C]

iii) High temperature tempering [500 – 700°C].

i) Low temperature tempering:

Martensite decomposes & gives low. Carbon martensite (tempered martensite) & transition Carbide called ε carbide [$Fe_{2.4}C$]

Martensite ⟶ Low Carbon Martensite + ε – Carbide.

It appears dark with common reagent, Nital & Picral (dark etching martensite)

Due to this hardness may increase. Brittleness decreases, No appreciable change in Retained Austenite.

ii) Medium temperature tempering:

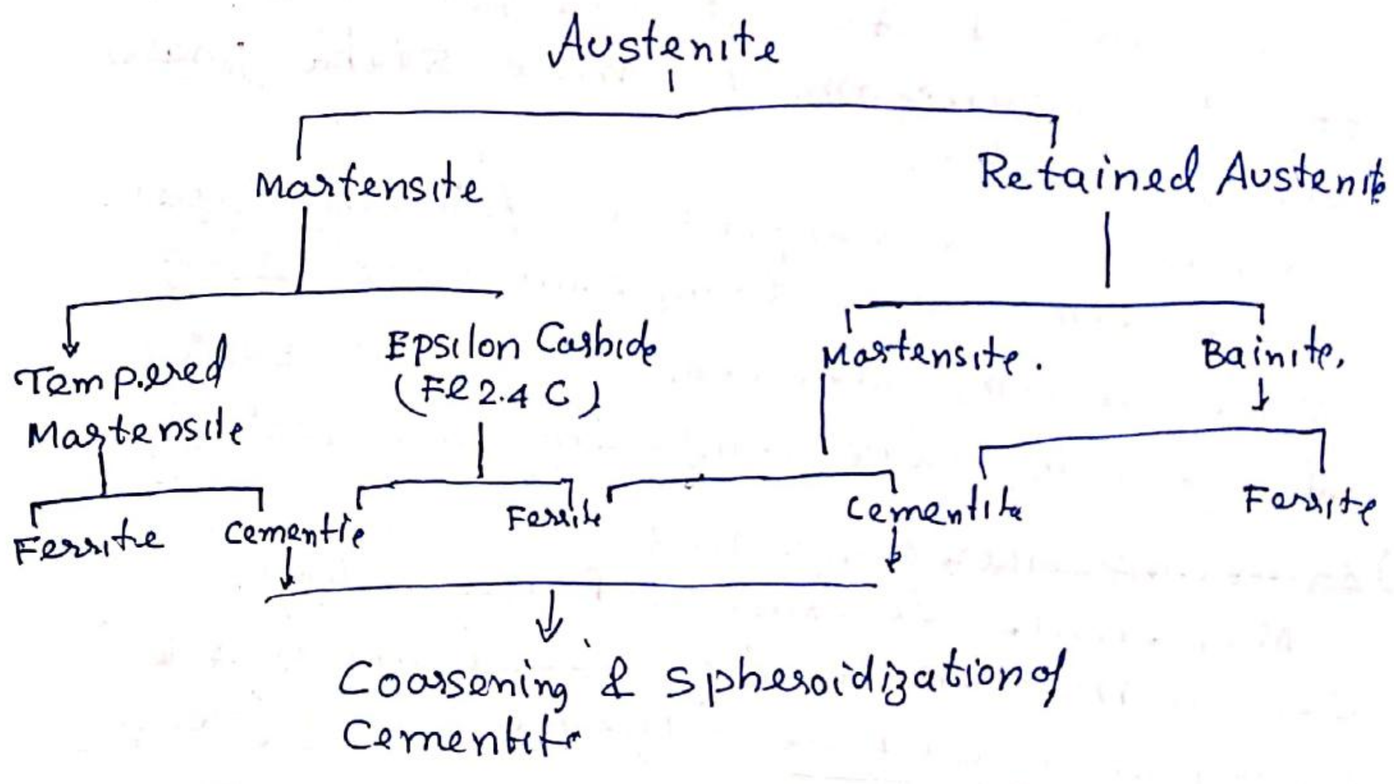
1) R A may get transformed to bainite. or decompose & form carbides & martensite.

II) The low carbon martensite & ε carbide transform to ferrite & cementite.

~~iii) High~~ These changes are accompanied by simultaneous increase in toughness & ductility.

III) High temperature tempering

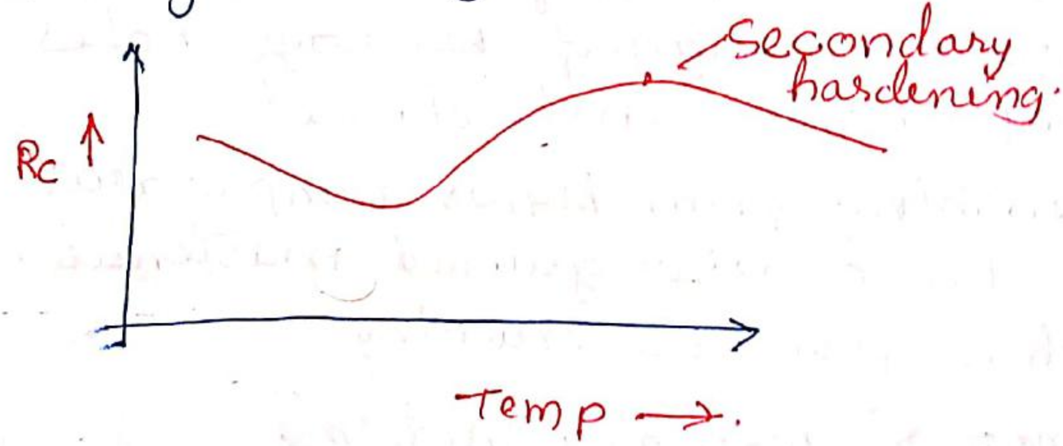
Cementite becomes coarse.



Auto tempering: Low CS have a high M_s temperature. So tempering of Martensite occurs during its formation from M_s to M_f.

Secondary Hardening.

for alloy steels containing Cr, W, Mo, V etc. hardness rises during tempering. due to. seperation of very hard complex alloy. carbides from martensite. This is called secondary hardening.



Temper Embrittlement.

Alloy steels containing Ni, Mn Cr when cooled slowly from temperature of 350° or. 550° become brittle in impact. Its due to seperation of some brittle phase.

This effect can be suppressed during rapid cooling.

Steels tempered above 350° C appear blue in colour & hence it called as blue brittleness.

Quench cracks

During quenching, surface of components cools rapidly than the centre, this results in non uniform volume changes; so leading to cracks

The following are the possible reasons of the quench cracks.

i) Excessive amount of non-metallic inclusion.

ii). Banded microstructure in steels: Due to alternate bands of ferrite & pearlite

iii) Improper selection of the steel.

iv) Improper design of key ways, holes sharp changes in structure etc.

v) Quenching from higher temperature leads to coarse grained martensite which is prone to cracking

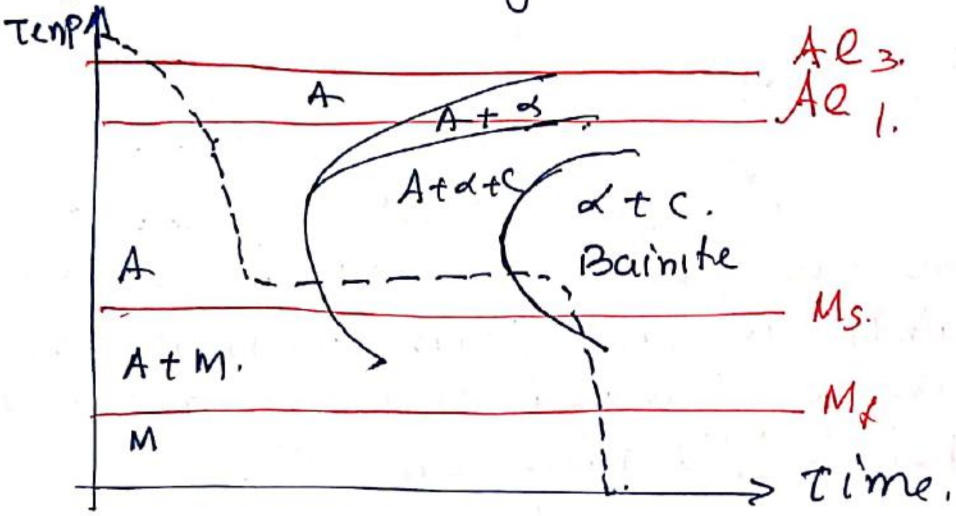
vi) Improper quenching mediums.

vii) Time delay between hardening & tempering operations.

Other heat treatments.

1) Austempering.

Cooling done in such way as to pass through bainitic region.



Properties of bainite are intermediate to those of martensite & pearlite & are very much similar to that of tempered martensite, so there is dimensional stability as there wont be RA.

The following are the disadvantages

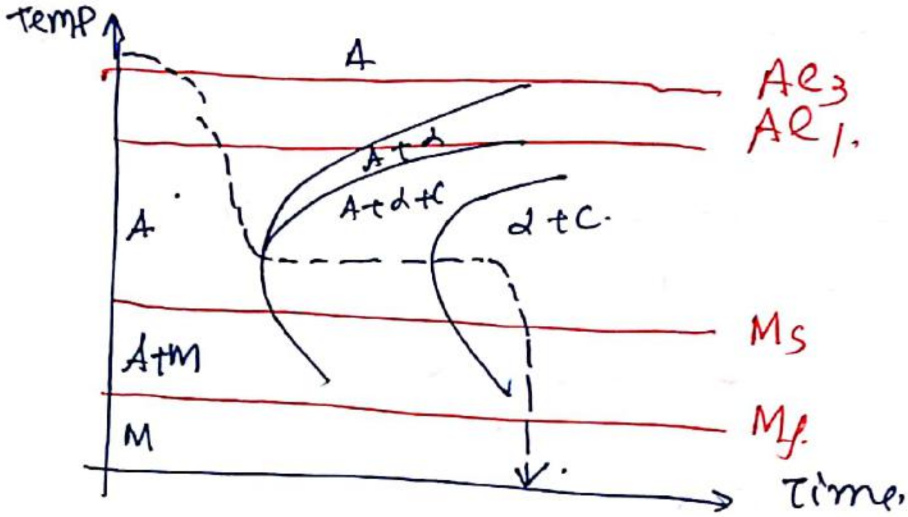
1) The hardness produced is not so high as that of martensite.

ii) Since critical cooling rate has to be exceeded, its applicable only to slightly high hardenability steels.

iii) Holding times are long & hence the process is expensive.

ii) Patenting:

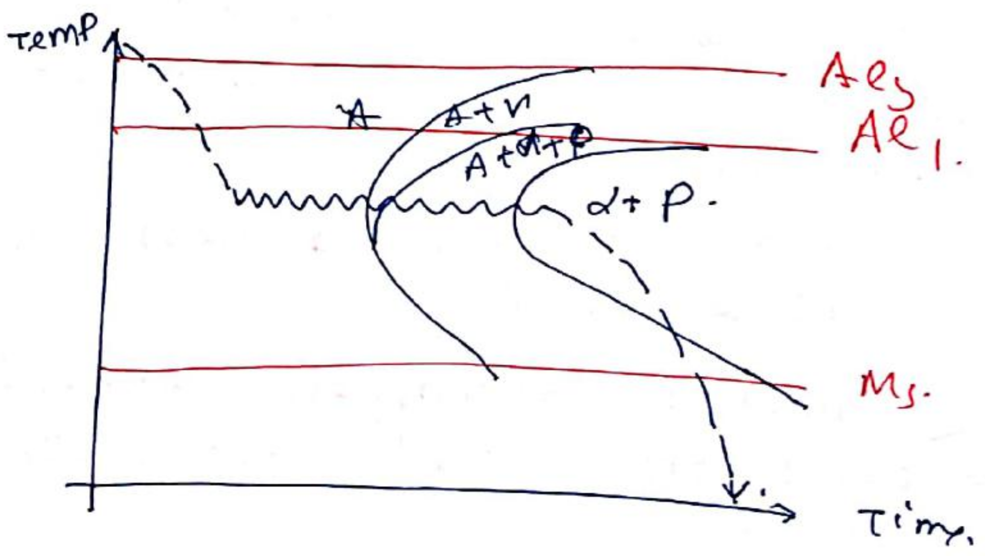
Similar to Austempering except the range of temperature used is for isothermal transformation



Microstructure produced vary from pearlite to upper bainite as the transformation temperature is lowered slightly above the nose to below the nose on TTT.

This process is used in wire drawing industry. because microstructure has good toughness. The wire can be drawn to ~~g o~~ 90%. area without intermediate heat treatment.

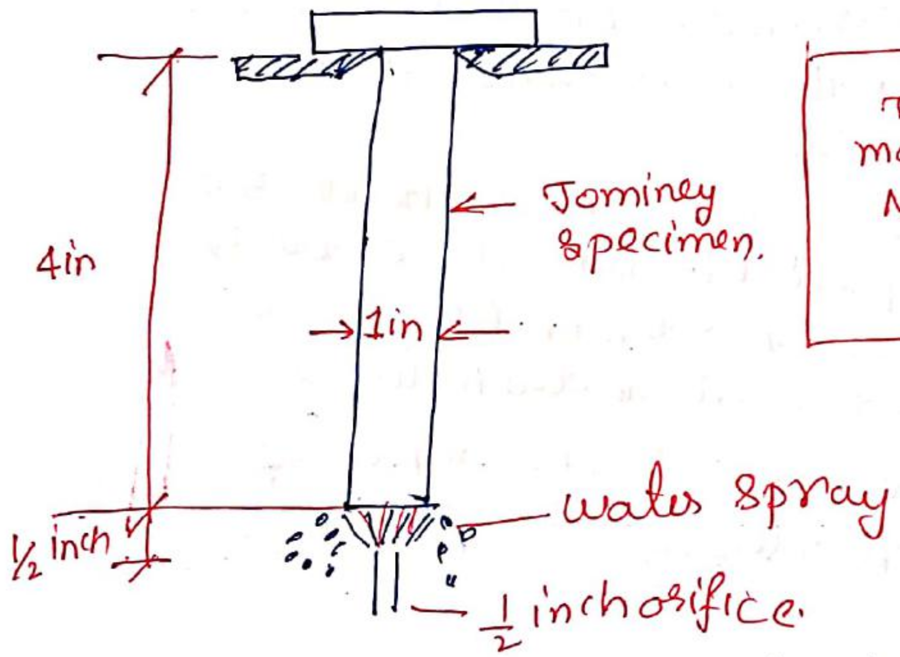
iii) Isoforming : Austenite is worked or, forged at Isothermal transformation temperature.



Hardenability

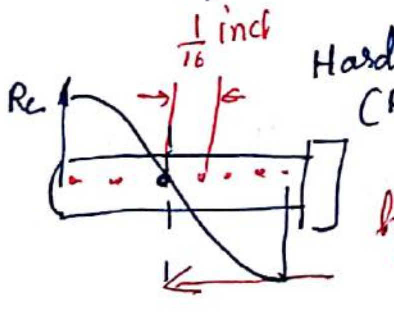
Hardenability is the ease with which a steel piece can be hardened by martensitic transformation or its the depth of hardening produced under the given conditions of cooling.

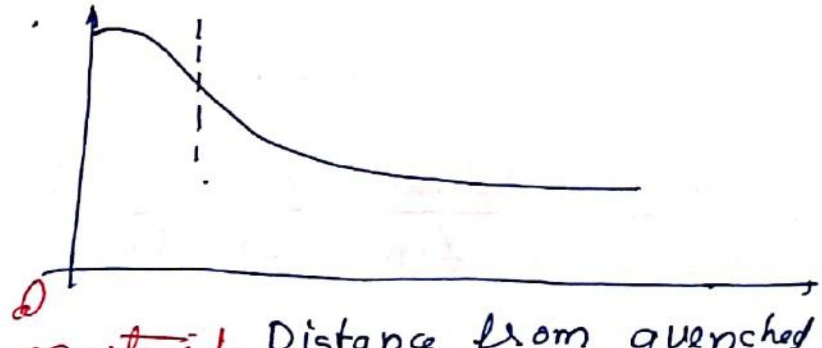
Hardenability is measured by Jominy End quench Test.



The hardness changes most rapidly at 50% Martensite.

specimen is austenized for a fixed time & temp & transfered to a fixture & water sprayed from bottom.
so variable cooling rate along the length.
(Martensite to Normalisation rate)
↓
@ quenched end.



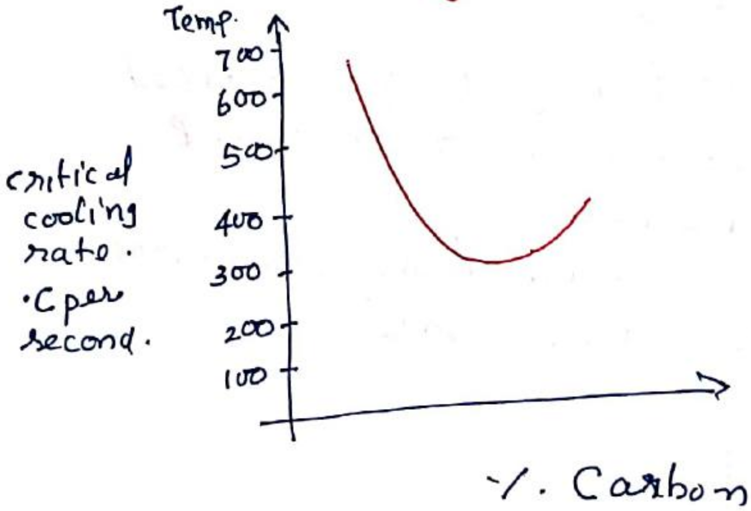


Hardenability can be measured by Grossman's method also.

In this method a numbers of cylindrical pieces of different dia of the same steel are heated to the same austenitizing temperature & quenched. The length of test pieces is kept more than 5 times of their dia. to avoid end effects. The test pieces are cut in the centre of the length & cross sections are examined for microstructure.

samples of small dia will get through hardened & show martensite in the centre. Large dia samples will show some or all pearlite at the centre.

The dia of the piece which shows 50% martensite & 50% pearlite at the centre is taken as measure of hardenability. This diameter is called critical diameter. & gives an idea about the depth of hardenability hardening.



Jominy hardenability test is most commonly used test to find out the hardenability of steel.

Hardenability can be approximated as.

$$J = 74C + 14Cr + 16Mn + 5.4Ni + 29Mo - 6.8S + 7HR_c.$$

[J → Hardness in HR_c].

The maximum hardness that can be obtained in steel largely depends on its carbon content whereas, its hardenability depends on the content of alloying elements.

<u>Assignment</u>

1. Explain in detail Transformation process of Austenite to Pearlite
2. Explain in detail Transformation process of Austenite to Martensite
3. What is the impact of Percentage on Carbon on TTT
4. State the conditions required for the formation of Bainite
5. State the difference between CCR and CCT
6. Why is the process of Tempering done on Ferrous Materials
7. What are Quench Cracks
8. What is Hardenability
9. Explain the process of Isoforming
10. Write the advantages and Disadvantages of Retained Austenite